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Hydrodynamical analysis of single inclusive spectra and Bose-Einstein correlations for $Pb + Pb$ at 160 AGeV

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Abstract

We present the first analysis of preliminary data for $Pb + Pb$ at 160 $AGeV$ using 3+1-dimensional relativistic hydrodynamics. We find excellent agreement with the rapidity spectra of negative hadrons and the correlation measurements. The data indicates a large amount of stopping; 65% of the invariant energy of the collision is thermalized and 73% of the baryons are contained in the central fireball. Within our model this implies that a quark-gluon-plasma of lifetime 3.4 fm/c was formed.

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In the ongoing quest for a quark-gluon plasma, experiments are being pursued using ever higher energies or masses in order to increase the lifetime of the system either by increasing the initial energy density or the size of the system. The probability of preparing a strongly interacting system that shows thermodynamical behaviour and therefore is treatable by well known thermodynamical or fluid dynamical methods increases with the size of the system. Recently, preliminary results were announced from the NA49 Collaboration [1, 2, 3] for $Pb+Pb$ central collisions at 160 $AGeV$. The application of Bjorken's estimate [4] of the initial energy density yields a value of 3 GeV/fm^3[1]. Of course, this estimate which is based on the value of one single observable (the rapidity density of the transverse energy in the central region) is no substitute for a comprehensive hydrodynamical study that takes into account all available data on spectra and correlation functions for different particle species. In this paper we present results of the first analysis of $Pb+Pb$ at 160 $AGeV$ using relativistic fluid dynamics and assuming an equation-of-state containing a phase transition.

A fully three-dimensional solution of the hydrodynamical relativistic Euler-equations was obtained with the computer code HYLANDER [5]. With this solution it is possible to reproduce [6] simultaneously mesonic and baryonic rapidity and transverse momentum spectra of the $S+S$ reaction at 200 $AGeV$ [7]. Corresponding measurements had been performed by the NA35 Collaboration. Based on these fits to the measured spectra, predictions were made for Bose-Einstein correlation functions[8, 9]. Those predictions agree quantitatively with the measurements[3, 10]. The model also reproduces the photon data for $S+Au$ collisions at SPS energies[11] and gives a simple explanation for the "soft-$p_\perp$ puzzle" [12] and the complex behaviour of the radii extracted from pion and kaon correlations and explained the difference in the extracted radii for pions and kaons in terms of a cloud of pions stemming from resonance decays, which surrounds the fireball (pion halo) [8]. In this paper we pursue a similar description for $Pb+Pb$ at 160 $AGeV$ reaction.

HYLANDER uses an initial scenario located between the extremes of the Landau[13] and the Bjorken[4] initial conditions. One has to specify an equation of state and a set of parameters which describe the initial conditions. Our equation of state exhibits a first order phase transition at a

critical temperature $T_C = 200\,MeV$ (*cf.* ref.[14]).

In the following we briefly sketch the basic features of the model which was introduced in ref. [6]. We assume that an initial reaction of two baryonic fluids leads to a deceleration of the two baryonic currents and to the spread of their width in momentum space. The kinetic energy is converted into internal excitation (thermal energy) of a third fluid which is created in the central region. The parameters determine the position of the maximum, the width in momentum space of the two baryonic fluids after the collision and the spatial extent of the central fireball. All other quantities are obtained from energy-momentum conservation (see table 1). The parameters are determined by fitting the pion rapidity spectrum; all other spectra are predictions of the model.

In Fig. 1a is shown the measured rapidity spectrum from the NA49 Collaboration [1, 2] of negative hadrons for $Pb+Pb$ central collisions at 160 $AGeV$. In table 1 we show the parameter set and the related physical quantities of the initial fireball as described in ref. [6] and compare them to the $S+S$ case. The $Pb+Pb$ system leads to a larger stopping than does $S+S$ and this results also in the increase of the inelasticity in $Pb+Pb$ compared to $S+S$.

In the following we discuss some of the results for the single- and double-inclusive spectra of hadrons and mesons. All calculations are based on thermal as well as on chemical equilibrium. In both types of spectra we include the effect of resonance decays. The influence of partial coherence [9] will not be considered here. A detailed analysis $Pb+Pb$ at 160 $AGeV$ will be published in ref.[15].

Consistent with expectation the degree of stopping and thermalization is higher in $Pb+Pb$ and the amount of thermal energy in the central fireball increases from 43% ($S+S$) to 65% ($Pb+Pb$). Due to the higher stopping, 73% of the baryons are located now in the central region compared to only 49% in the $S+S$ case. The location of the maximum density of the two baryon currents y_m in rapidity space is significantly shifted into the central rapidity region. It is important to note that the baryons for $Pb+Pb$ are almost stopped. The resulting high baryonic density of 2.14 fm^{-3} in the center and 3.2 fm^{-3} in the forward region is three times higher than in $S+S$ and can

therefore no longer be neglected. It will have a strong influence on strangeness, photon and lepton production as well as on the relative meson abundancies.

The maximum lifetime of the fireball is increased from 6.9 fm/c ($S+S$) up to 14.5 fm/c for $Pb+Pb$. We observe approximately the same behaviour for the lifetimes of the QGP. Whereas in $S+S$ the lifetime of the QGP was short (1.5 fm/c), in the $Pb+Pb$ case a QGP persists for 3.4 fm/c [1]. Taking into account that the initial volume of the $Pb+Pb$ system is $\sim$ eight times larger than in the $S+S$ case, we note that the lifetime increases slower than does the volume. This effect is due to the cooling by transverse rarefaction waves which are only sensitive to the difference in the transverse radius which differs approximately by a factor two from $S+S$ to $Pb+Pb$.

For $Pb+Pb$ at 160 $AGeV$ we find average values for the baryonic chemical potential $\langle\mu_B\rangle = 363 MeV$ and for the strangeness chemical potential $\langle\mu_S\rangle = 69\, MeV$ using $T_f = 139\, MeV$ for the freeze-out temperature. As a result we obtain a chemical composition of 48.9% thermal (directly emitted) pions, 15.4% thermal kaons, 21.6% mesons (such as ρ, ω, η, $K^\star$, ... etc.), 13.7% baryons (such as p, Δ, Σ, Λ, ... etc.) and 0.4% anti-baryons (such as $\bar{p}, \bar{\Delta}$, ... etc.). The detailed sub-fractions will be given in ref.[15]. The corresponding values for $S+S$ at 200 $AGeV$ are given in ref.[6].

The calculation of single particle inclusive spectra with HYLANDER was extensively discussed in ref.[6]. Fig. 1a shows our model predictions for negative thermal π^- compared to all negative π. We stress that due to our choice of the freeze-out temperature of $T_f = 139\, MeV$, there are large resonance contributions ($40\% - 50\%$) to the pionic spectra. The rest of our rapidity spectrum of negative hadrons h^- is made up by contributions from negatively charged kaons. The K^- spectrum consists mainly of directly emitted kaons; less than 10% come from the $K^\star$ resonance.

The h^- rapidity spectrum has been chosen to fit the NA49 data in such a way that the proton rapidity spectrum has the shape observed in the NA44 experiment[16]. Since it is not clear from the NA44 experiment to what extent Λ decays appear in the proton production, we show our results

[1] We mention that even for those who do not believe in hydrodynamics, this value is an upper limit.

for the proton rapidity spectra with and without contributions from the Λ decay. Within these limits we reproduce the results for the NA44 proton rapidity spectra.

Transverse momentum spectra are shown in Fig. 1b. They were not involved in finding a parameter set for the fit of experimental data and are therefore predictions.

The calculation of Bose-Einstein correlations (BEC) was performed using the formalism outlined in refs. [8, 9, 17] including the decay of resonances. The hadron source is assumed to be fully chaotic. We present results for both pion and kaon BEC.

In the previous section we mentioned that in the case of pion interferometry we have to deal with a large fraction – 40% to 50% – of the pions originating from resonances. The effects of resonance decays on two-particle Bose-Einstein correlation functions are shown in Fig. 2. We show examples of correlation functions in the longitudinal and transverse directions. The K and q variables indicate our choice of $K^\mu = \frac{1}{2}(k_1^\mu + k_2^\mu)$ and $q^\mu = k_1^\mu - k_2^\mu$ to be the average and the relative 4-momentum of the particle pair with 4-momenta k_1^μ and k_2^μ. The contributions from resonance decays are successively added to the correlation function of thermal π^-.

By adding several interferometry contributions from resonance decays, the correlation functions become narrower reflecting a larger effective source size. We point out that the effect of the ω resonance is clearly visible within experimental resolution ($\sim 5\ MeV/c$), although its lifetime τ_ω is rather large ($\tau_\omega = 23.4\ fm/c$) compared to the spatial dimensions of the fireball[2]. The decay of the ω resonance is also mainly responsible for the deviation of the functional shape of the correlation function from an approximately Gaussian shape. Another important feature of resonance decay effects is the appearance of η decays. Due to the very large lifetime ($\tau_\eta = 1.64 \times 10^5\ fm/c$) of the η resonance, the two-particle correlation function becomes so narrow that the result is a decrease in the experimental resolvable intercept to values below 1.80, depending on the

[2]This is in contrast to ref.[18] where the contribution of the ω resonance was found to be invisible.

experimental resolution[3] (*cf.* [9]).

In order to extract effective hadron source radii, we fit our results to the Gaussian form used by experimentalists (for the choice of the variables, cf., e.g. ref.[9]):

$$C_2(\vec{k}_1, \vec{k}_2) \;=\; 1 \;+\; \lambda \;\exp\left[-\frac{1}{2}(q_\|^2 R_\|^2 \;+\; q_{side}^2 R_{side}^2 \;+\; q_{out}^2 R_{out}^2)\right] \;. \tag{1}$$

It should be emphasized that here λ does *not* represent the effect of coherence, but the effective reduction of the intercept due to the contributions from η decays.

Fig. 3a shows our predictions for effective radii $R_\|$, R_{side} and R_{out} as functions of rapidity and transverse momentum of the pair, both for $\pi^-\pi^-$ (solid lines) and for K^-K^- pairs (dashed lines). For comparison, we have also included the curves for thermally produced pions (dotted lines). In the case of interferometry of negative kaons, we checked that the $K^\star$ resonance gives negligible contributions to the two-particle BECs. It is also seen that the direct (thermal) pions, which can barely be separated experimentally from the pions from resonance decay, show a very similar behaviour as do the radii extracted from kaon interferometry. It is again a confirmation that kaon interferometry probes the spatial and temporal characteristics of the fireball whereas pion interferometry probes the halo due to resonances.

The general features of the momentum-dependent effective radii which were presented in refs.[8, 9] for $S+S$ at 200 GeV hold also for $Pb+Pb$ at 160 $AGeV$. We stress four observations:

(i) In the case of pion interferometry, the resonance decays increase the effective radii by almost the same factors as for $S+S$ at 200 $AGeV$ (~ 2.1 in the longitudinal and ~ 1.4 in transverse direction).

(ii) The difference between the kaon and pion radii determines the size of the resonance halo. Its maximum extension is 5.6 fm in longitudinal direction, 2.4 fm in side- and 2.6 fm in out directions

[3] The true intercept is still two for the single correlation function, i.e. a correlation function which contains thermal as well as resonance contributions.

(compare corresponding values for $S+S$ at 200 $AGeV$ in table 1). The halo size in the longitudinal direction is larger because here we have stronger retardation effects due to the delayed resonance decay because of high fluid velocities.

(iii) We note that the Sinyukov-formula (*cf.* ref.[19]) fails to describe our results although it was derived from hydrodynamical assumptions. The reason for the difference is that Sinyukov's formula was obtained for a longitudinally expanding source which is better described in terms of the Bjorken scenario. In the case of $Pb+Pb$ we have more stopping and thus a larger transverse expansion compared to $S+S$. For $S+S$ at 200 $AGeV$ we found a maximum transverse velocity $u_\perp^{max}(S) = 0.43$ whereas for $Pb+Pb$ at 160 $AGeV$ we obtain $u_\perp^{max}(Pb) = 0.61$. Sinyukov's approach is therefore too rough, and this results in the deviations. It also suggests that it is dangerous to overstress the Bjorken approach because it can lead to misleading or inconsistent results.

(iv) The correlation functions are measurable with the experimental resolution of the detector setups. Even the influence of the ω should be visible.

In Fig. 3b we show our results for effective radii as a function of the average transverse momentum $K_\perp$ of the pair for all pions at $y_K = 4.5 - y_{cm} = 1.6$. In particular, the effective longitudinal radii $R_{\|}$ are evaluated in the longitudinal comoving system (LCMS) in order to make a comparison to preliminary NA49 measurements [3] possible. Our calculations agree surprisingly well with the data.

To summarize: we have shown that preliminary data of the NA49 Collaboration can be reproduced with a self-consistent three-dimensional relativistic hydrodynamic description assuming an equation of state with a first order phase transition. We have made predictions for rapidity spectra of pions, kaons and protons for $Pb+Pb$ at 160 $AGeV$. Our data analysis indicates a stronger stopping and an enhanced transverse flow in the case of $Pb+Pb$ collisions. The high baryon density in the central region will have a strong influence on the chemistry of the fireball and can no longer be neglected [15]. Models dealing with weak probes and particle abundancies need to take this into account.

Bose-Einstein correlation functions for pions and for kaons have also been predicted. It is important to note that in the case of the pion interferometry, the presence of a resonance halo increases the size of the fireball in the central region by factors ~ 2.1 in longitudinal and ~ 1.4 in transverse direction. The NA49 data on interferometry, which were presented in terms of inverse radii, are surprisingly well described.

The results of this work constitute further evidence that heavy-ion collisions in the SPS region show fluid dynamical behaviour and that the assumption of a first order phase transition from QGP to hadronic matter is necessary in order to reproduce the data as was first pointed out in [5] and later confirmed by several independent groups [20].

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Figure Captions

Fig. 1a Rapidity spectra for negative hadrons (h^-), negative pions (π^-), negative thermal pions ($th.\,\pi^-$), protons (p), protons without those from Λ decay ($p\backslash\Lambda \to p$), negative kaons (K^-) and negative thermal kaons ($th.\,K^-$). The data points are preliminary results of the NA49 Collaboration for negative hadrons from central $Pb + Pb$ collisions at 160 $AGeV$. Circles (diamonds) stand for the measurements from the VTP2 (MTPC) (*cf.* refs.[1],[2]).

Fig. 1b Transverse momentum spectra for negative hadrons (h^-), negative pions (π^-), negative thermal pions ($th.\,\pi^-$), protons (p), protons without those from Λ decay ($p\backslash\Lambda \to p$), negative kaons (K^-) and negative thermal kaons ($th.\,K^-$).

Fig. 2 Distortion of the Bose-Einstein correlation functions of negatively charged pions through resonance decays. The contributions from resonance decays are successively added to the correlation function of thermal π^- (dotted lines "1"). The resultant correlation functions of all π^- are given by the solid lines.

Fig. 3a Dependence of the longitudinal and transverse radii (extensions of emission zones) extracted from Bose-Einstein correlation functions on the rapidity y_K and transverse average momentum $K_\perp$ of the pair. The curves are for all π^- (solid lines), thermally produced π^- (dotted lines) and K^- (dashed lines).

Fig. 3b Effective radii extracted from Bose-Einstein correlation functions as a function of the transverse average momentum $K_\perp$ of the pair for all pions at rapidity $y_K = 4.5 - y_{cm} = 1.6$. The longitudinal effective radii are shown in the LCMS. The data points are preliminary results of the NA49 Collaboration [3].

Table Caption

Table 1 Properties of initial fireball, extracted from a hydrodynamical analysis of the $S+S$ NA35 data [7] and the $Pb+Pb$ NA49 data [1],[2].

	S+S	Pb+Pb
Fit parameters		
Thermal energy in the central fireball	0.43	0.65
Longitudinal extension of central fireball	0.6 fm	1.2 fm
Rapidity at edge of central fireball	0.9	0.9
Rapidity at maximum of initial baryon distribution	0.82	0.60
Width σ of initial baryon y distribution	0.4	0.4
Output		
fraction of baryons in central fireball	0.49	0.73
initial energy density	13 GeV/fm^3	20 GeV/fm^3
max. lifetime	6.9 fm/c	13.5 fm/c
lifetime of QGP	1.5 fm/c	3.4 fm/c
max. halo-size in “longitudinal” direction	2.5 fm	5.6 fm
max. halo-size in “side” direction	1.0 fm	2.4 fm
max. halo-size in “out” direction	1.3 fm	2.6 fm

Table 1